

DOT/FAA/AR-04/15

Office of Aviation Research
Washington, DC 20591

Comparison of Various Impedance Measurement Techniques for Assessing Degradation in Wiring Harness Shield Effectiveness and a Field Survey of FADEC Shield Integrity of In-Service Aircraft

October 2004

Final Report

This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.



U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or use thereof. The United States Government does not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the objective of this report. This document does not constitute FAA certification policy. Consult your local FAA aircraft certification office as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

1. Report No. DOT/FAA/AR-04/15		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle COMPARISON OF VARIOUS IMPEDANCE MEASUREMENT TECHNIQUES FOR ASSESSING DEGRADATION IN WIRING HARNESS SHIELD EFFECTIVENESS AND A FIELD SURVEY OF FADEC SHIELD INTEGRITY OF IN-SERVICE AIRCRAFT				5. Report Date October 2004	
				6. Performing Organization Code	
7. Author(s) J.B. O'Loughlin and S.R. Skinner				8. Performing Organization Report No.	
9. Performing Organization Name and Address National Institute for Aviation Research Wichita State University 1845 Fairmount Avenue Wichita, KS 67260-0093				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. 00-C-WSU-00-28	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code AIR-100	
15. Supplementary Notes The FAA William J. Hughes Technical Center Technical Monitor was Anthony Wilson.					
16. Abstract <p>This report compares the performance of various impedance measurement techniques for measuring degradation in wire harness shield effectiveness. For field measurements, comparisons were made between a Boeing loop resistance tester (LRT) and a Hewlett-Packard (HP) network analyzer. For laboratory measurements, comparisons were made between an HP network analyzer, a Boeing LRT operating at 200 Hz, an Airbus LRT operating at 1000 Hz, and a Keithley Model 580 Micro-Ohmmeter.</p> <p>In the field survey, the electrical characteristics of shielded wire bundles of an aircraft's critical system were analyzed for increase in shield loop resistance from time of manufacture through 5 years of service. Full Authority Digital Engine Control (FADEC) wire harnesses from general aviation business jet aircraft were chosen for this shield degradation field survey.</p> <p>The results of the loop impedance measurement techniques investigation and analysis of the FADEC field survey data were</p> <ul style="list-style-type: none"> • A loop resistance meter, operating at either 200 or 1000 Hz, was found to be as effective as the swept-frequency network (impedance) analyzer for detecting the types of wire harness shield degradation studied in this project because the harness transfer impedance remains largely resistive at frequencies below 2000 Hz. • The loop resistance meter was found to be more practical for routine field inspection than the network analyzer due to its portability, simpler usage, and less amount of measurement time. However, both techniques require a skilled operator. • Lightning and high-intensity radiated fields protection degrade when the loop resistance of shields connecting equipment and aircraft structures increases. • The field survey data showed that the average shield resistance of FADEC harnesses increased with both aircraft age and flight hours, from 8 milliohms at manufacture to a maximum of 12.5 milliohms 4 years later, somewhat independent of flight hours. The change in loop resistance correlated better with aircraft age (0.94) than it did with aircraft flight hours (0.68). 					
17. Key Words Backshell, Connector, Field survey, Hand loose, Harness, Loop resistance, Overbraid, Shield degradation			18. Distribution Statement This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.		
19. Security Classification (of this report) Unclassified		20. Security Classification (of this page) Unclassified		21. No. of Pages 45	22. Price

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical assistance, guidance, and review given this study by Billy M. Martin, Charles B. Beuning, Michelle M. Cronkleton, and Michael D. Reilly of the Cessna Aircraft Company, without whose support this effort would not have been possible.

Special thanks is also given to the Wichita State University graduate research assistants, Syed Ghayur, Ghulam Awan, Najma Begum, and Fayyaz Khan, who carefully and laboriously collected and organized the data, and professionally and methodically worked through numerous iterations and revisions to help produce this report.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	ix
1. INTRODUCTION	1
2. MEASUREMENT TECHNIQUES	1
2.1 Boeing LRT	1
2.2 Airbus LRT (TS 11194)	3
2.3 Hewlett-Packard Network Analyzer	4
2.4 Keithley Model 580 Micro-Ohmmeter	5
3. FIELD SURVEY	8
3.1 System Selection	8
3.2 Full Authority Digital Engine Control System Description	8
3.3 Test Procedure	8
3.3.1 Measurements on the FADEC Wire Bundles	8
3.3.2 Measurements	12
3.3.3 Observations	13
4. COMPARISON OF IMPEDANCE MEASUREMENTS TECHNIQUES AND NETWORK ANALYZER RESULTS	13
4.1 Comparison of Measurements on Actual Aircraft Wiring	13
4.1.1 Measurements	14
4.1.2 Observations	15
4.2 Comparison of Measurements on Laboratory Test Panels	16
4.2.1 Resistance-Inductance-Resistance Modeling for Test Panels	17
4.2.2 Measurements	18
4.2.3 Observations	23
5. OVERALL OBSERVATIONS	23
6. REFERENCES	24
7. GLOSSARY	24

LIST OF FIGURES

Figure		Page
1	Boeing LRT	1
2	Boeing LRT Measuring Aircraft Wiring Resistance	2
3	Coupler Probes Attached to the Boeing LRT	3
4	Test Setup for the Airbus LRT	4
5	Hewlett-Packard Network Analyzer Test Setup for Loop Impedance Measurement	5
6	Keithley Model 580 Micro-Ohmmeter	5
7	Direct Current Resistance Test Locations (Center Connector)	6
8	Direct Current Resistance Test Location (End Connector)	7
9	Locations of FADEC Unit Measurements	11
10	Loop Resistance Tester Measurements on FADEC Unit	11
11	The FADEC Wire Harness	11
12	The FADEC Harness Loop Resistance vs Age of the Aircraft	12
13	The FADEC Harness Loop Resistance vs Flight Hours on the Aircraft	12
14	Boeing LRT Measurements on the FADEC Wire Bundles	14
15	Network Analyzer Measurements on the FADEC Wire Bundles	14
16	Comparison of LRT and Network Analyzer Measurements on Aircraft FADEC System	15
17	Individual Loop Resistance Measurement Using the LRT	16
18	Individual Loop Impedance Measurement Using the Network Analyzer	16
19	Circuit Diagram for R-L-R Modeling	17
20	Example of Total Loop Impedance Characteristics Before and After Degradation Test Using the Network Analyzer	20
21	Total Loop Impedance Characteristics Before and After Mechanical Degradation Test (Test Panel B1)	21

22	Loop Resistance Comparison at a High-Severity Test Level	22
23	Loop Resistance Using Different Measurement Techniques	22

LIST OF TABLES

Table		Page
1	Loop Resistance Measurements on FADEC Wire Bundles of In-Service Aircraft	9
2	Loop Resistance Measurements on FADEC Wire Bundles of New Production Aircraft	10
3	Measurement Comparison of LRT and Network Analyzer on Aircraft	15
4	Loop Resistance Comparison Using Different Techniques at Baseline and High Test Levels for Test Panels Type A	18
5	Loop Resistance Comparison Using Different Techniques at Baseline and High Test Levels for Test Panels Type B	19
6	Comparison of Loop Resistance Values Using Different Techniques	19
7	Statistics of Network Analyzer Measurements at 200 Hz and 300 kHz	21

LIST OF ACRONYMS AND SYMBOLS

Ω	Unit of resistance
k Ω	Kiloohms
$\mu\Omega$	Microohms
ac	Alternating current
dc	Direct current
FADEC	Full Authority Digital Engine Control
HP	Hewlett-Packard
L	Inductor
LED	Light-emitting diode
LRT	Loop resistance tester
P/N	Part number
RF	Radio frequency
R-L-R	Resistance-Inductance-Resistance
R _p	Parallel resistor
R _s	Series resistance
STBY	Standby

EXECUTIVE SUMMARY

This report presents a comparison of shield loop resistance measurement techniques for assessing degradation in wiring harness shield effectiveness and the results of a field survey of harness shield degradation in business jet aircraft engine control systems. This study was sponsored by the Federal Aviation Administration and conducted at the National Institute for Aviation Research at Wichita State University.

The study summarizes the performance of various resistance measurement techniques and compares their usefulness in a field environment versus laboratory environment. For field measurements, comparisons were made between a Boeing loop resistance tester (LRT) and a Hewlett-Packard (HP) network analyzer. For laboratory measurements, the comparisons were made between an HP network analyzer, a Boeing LRT operating at 200 Hz, an Airbus LRT operating at 1000 Hz, and a Keithley Model 580 Micro-Ohmmeter.

In the field survey, the electrical characteristics of shielded wire bundles of an aircraft's critical system were analyzed for increase in shield loop resistance. The electrical characteristics of a business jet aircraft's Full Authority Digital Engine Control (FADEC) were analyzed from the time of manufacture through 5 years of service.

The results of the loop resistance measurement techniques investigation and the 5-year analysis of FADEC harness shield degradation were

- A loop resistance meter, operating at either 200 or 1000 Hz, was found to be as effective as the swept-frequency network (impedance) analyzer for detecting the types of wire harness shield degradation studied in this project because the harness transfer impedance remains largely resistive at frequencies below 2000 Hz.
- The loop resistance meter was found to be more practical for routine field inspection than the network analyzer due to its portability, simpler usage, and less amount of measurement time. However, both techniques require a skilled operator.
- Lightning and high-intensity radiated fields protection degrade when the loop resistance of shields connecting equipment and aircraft structures increases.
- The field survey data showed that the average shield resistance of FADEC harnesses increased with both aircraft age and flight hours, from 8 milliohms at manufacture to a maximum of 12.5 milliohms 4 years later, somewhat independent of flight hours. The change in loop resistance correlated better with aircraft age (0.94) than it did with aircraft flight hours (0.68).

1. INTRODUCTION.

The purpose of this study was to analyze the shield degradation in aging aircraft and to compare the effectiveness of various loop impedance measurement techniques for field and laboratory use. In the field survey, the electrical characteristics of a shielded wire bundle of an aircraft's critical system were analyzed from the time of manufacture up to 5 years of service. The study was also done to check the performance of various impedance measurement techniques and to compare them for both field and laboratory use. For field measurements, the comparison was made between a Boeing loop resistance tester (LRT) and a Hewlett-Packard (HP) network analyzer. For laboratory measurements, the comparison was made between a network analyzer, a Boeing LRT, an Airbus LRT, and a Keithley Model 580 Micro-Ohmmeter. The results of the field survey and the laboratory testing have been analyzed in depth to draw some significant observations.

2. MEASUREMENT TECHNIQUES.

2.1 BOEING LRT.

The Boeing LRT measures the loop resistance of the electronic cable shielding as installed in the aircraft without having to disconnect the cables. It is capable of testing the cable shielding for all critical and essential airplane systems, including fly-by-wire systems [1]. The Boeing LRT is shown in figure 1.



FIGURE 1. BOEING LRT

The Boeing LRT is portable, easy to operate, and provides a nonintrusive testing technique that will not disturb the connectors. It can also be used to isolate a bad joint without removing the cables, but this feature was not used in this study. The LRT is comprised of four elements: drive current coupler, sense current coupler, joint probes, and an instrument assembly containing the LRT battery and processor. It operates at a low frequency of 200 Hz to minimize the effects of loop inductance, yet it provides good skin-depth penetration [1].

The basic principle of operation is that of an ideal transformer, which will transform impedance from the input of the transformer to the output. From figure 2 [2], which shows the schematic of a Boeing LRT as used for measuring the shield impedance of an aircraft wire bundle, the shield can be viewed as a conductive loop going through the structure, connector, cable shield, connector, and back to the structure. A coupler is connected to this loop, which acts as the output winding and magnetic core of a transformer, and the shielded cable forms the input winding of the transformer. A voltage is forced around the coupler winding, which results in a voltage around the shield loop. The impedance of the loop can be found by measuring the current around the loop. The drive coupler drives the voltage around the loop, and the sense coupler senses the current flowing in the loop to give shield loop impedance. Figure 3 shows both coupler probes connected to the Boeing LRT in order to make a loop measurement.

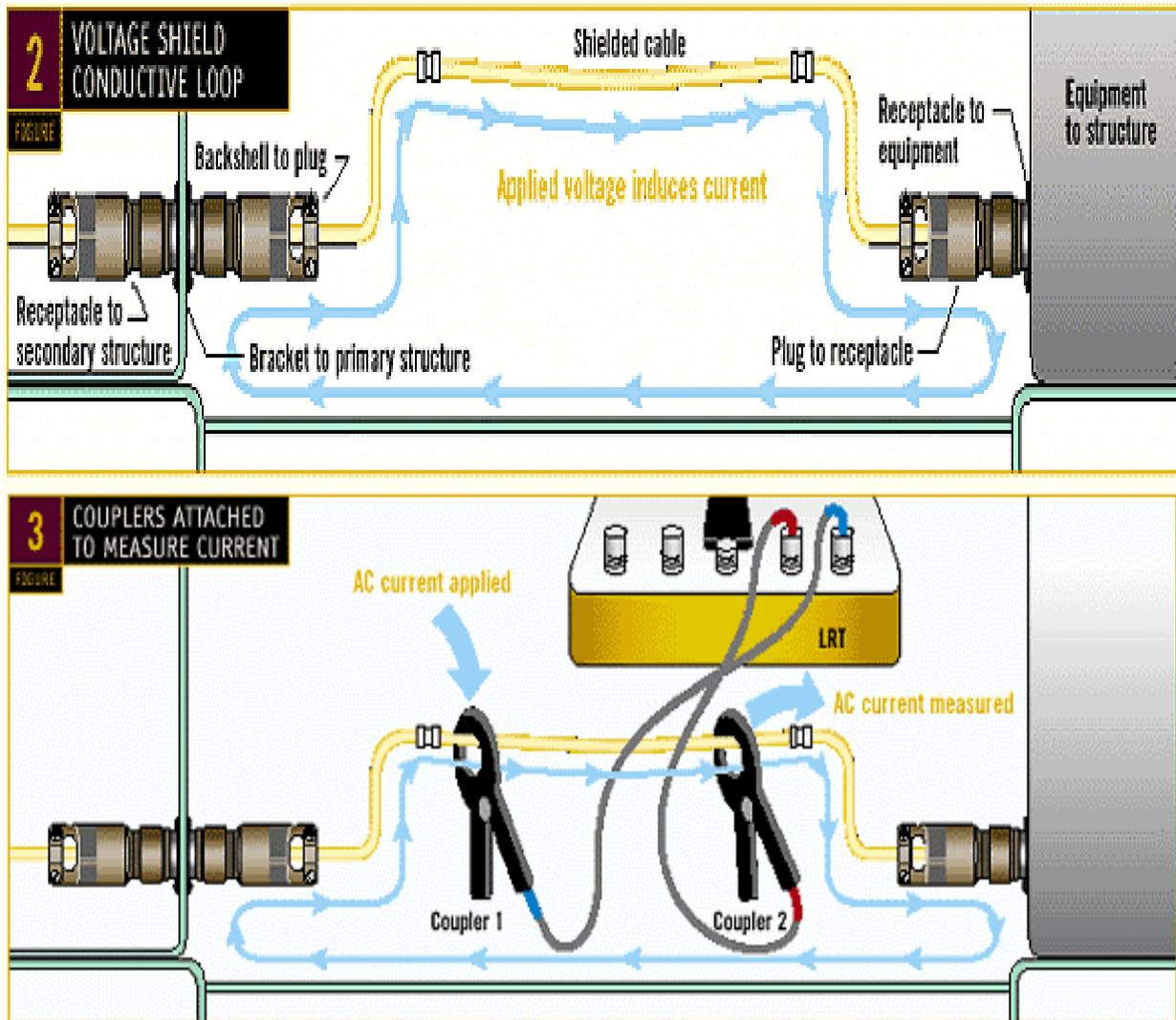


FIGURE 2. BOEING LRT MEASURING AIRCRAFT WIRING RESISTANCE

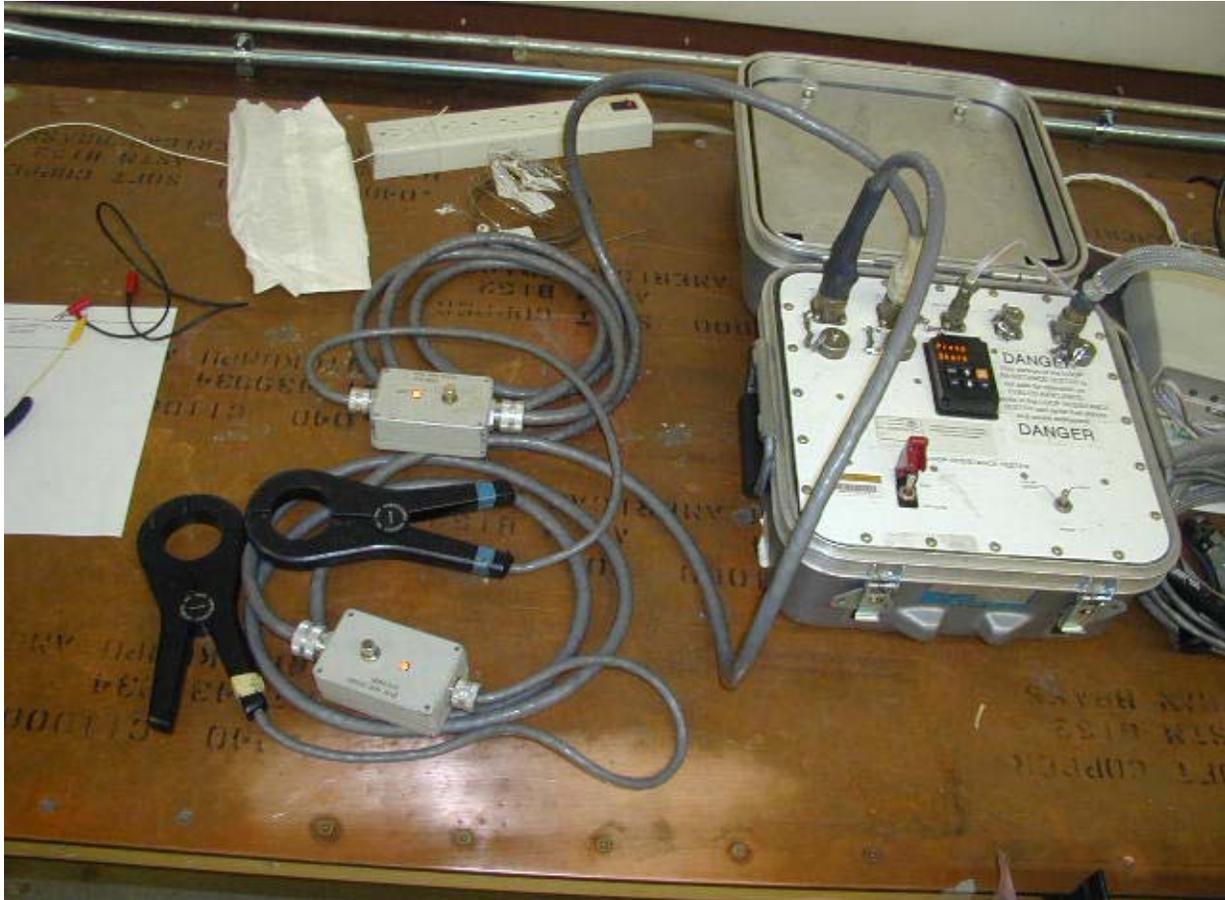


FIGURE 3. COUPLER PROBES ATTACHED TO THE BOEING LRT

2.2 AIRBUS LRT (TS 11194).

The Airbus LRT [3] operates at a fixed frequency of 1 kHz and measures the loop resistance of the electronic cable shielding, as installed in the aircraft, without disconnecting the cables. The LRT can also be used to isolate a bad joint without removing the cables, but this feature was not used in this study.

The tester is designed to measure the electrical resistance of closed loops by the induction of an alternating current (ac) into the loop, as shown in figure 4. The current is induced into the loop by a generator in a current injection source via a clip-on transformer, and it flows through the specimen, through the bonding connections of the specimen with the structure, and through the structure itself. In the normal operating mode, a current of 1 ampere is made to flow in the loop under test. The panel tester displays loop resistance directly in milliohms.

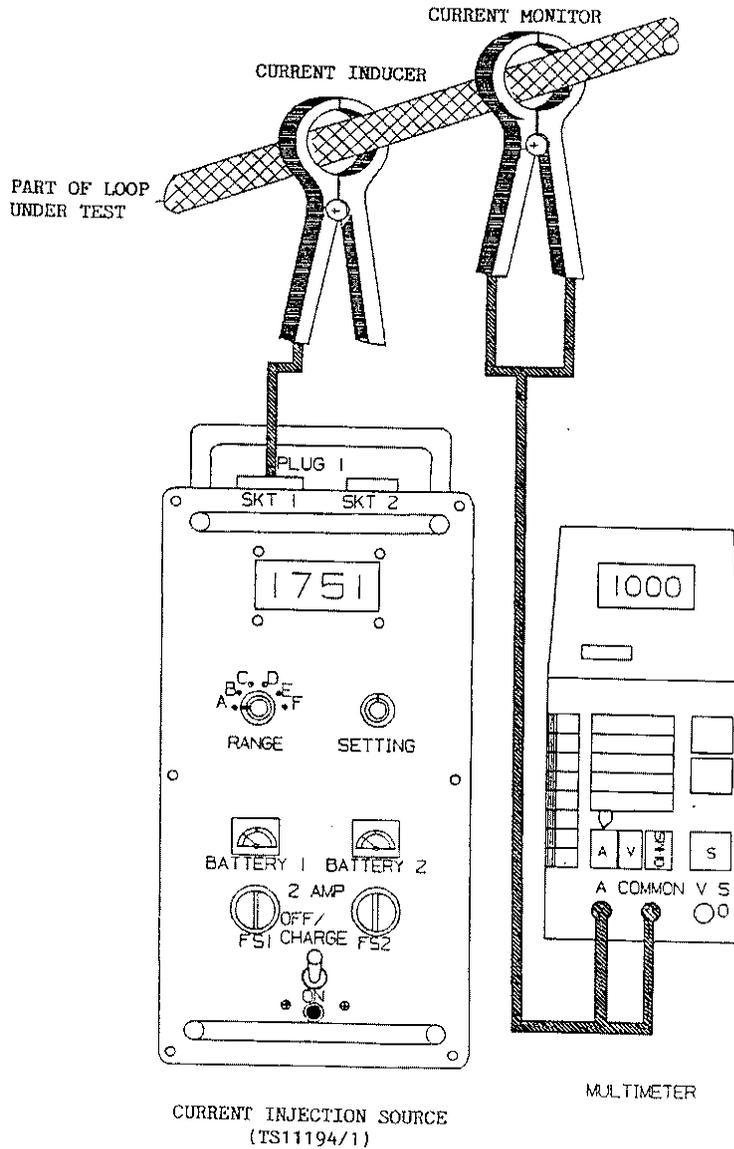


FIGURE 4. TEST SETUP FOR THE AIRBUS LRT

2.3 HEWLETT-PACKARD NETWORK ANALYZER.

The HP network analyzer was used to determine the loop impedance response over a range of frequencies selected from 10 Hz to 10 MHz.

The measurement setup was made using a Pearson Clamp-On Current Monitor (P/N 3525) and a Current Injection Probe (P/N CIP9136) clamped around the loop to be monitored. The radio frequency (RF) output from the network analyzer is connected to the Current Injection Probe, which is responsible for the current flow in the wire bundle through transformer action. The outputs from the Pearson Current Monitor and the Current Injection Probe are connected to the input ports of the network analyzer. The noise factor is subtracted from the real-time

measurements, which are used to calculate the loop impedance at that frequency. Figure 5 shows the network analyzer measurement setup.



FIGURE 5. HEWLETT-PACKARD NETWORK ANALYZER TEST SETUP FOR LOOP IMPEDANCE MEASUREMENT

The network analyzer uses a combination of front panel (hard keys) and soft keys. The hard keys are grouped by function and provide access to various soft key menus. These menus list the possible choices for a particular function, with each choice corresponding to one of the eight soft keys located to the right of the cathode-ray tube.

2.4 KEITHLEY MODEL 580 MICRO-OHMMETER.

A Keithley Model 580 Micro-Ohmmeter was used for low direct current (dc) resistance measurement requirements ranging from 10 microohms ($\mu\Omega$) to 200 kilohms ($k\Omega$). Figure 6 shows the microohmmeter with its leads.



FIGURE 6. KEITHLEY MODEL 580 MICRO-OHMMETER

Figure 7 specifies the dc resistance test locations on a center connector of a laboratory test panel.

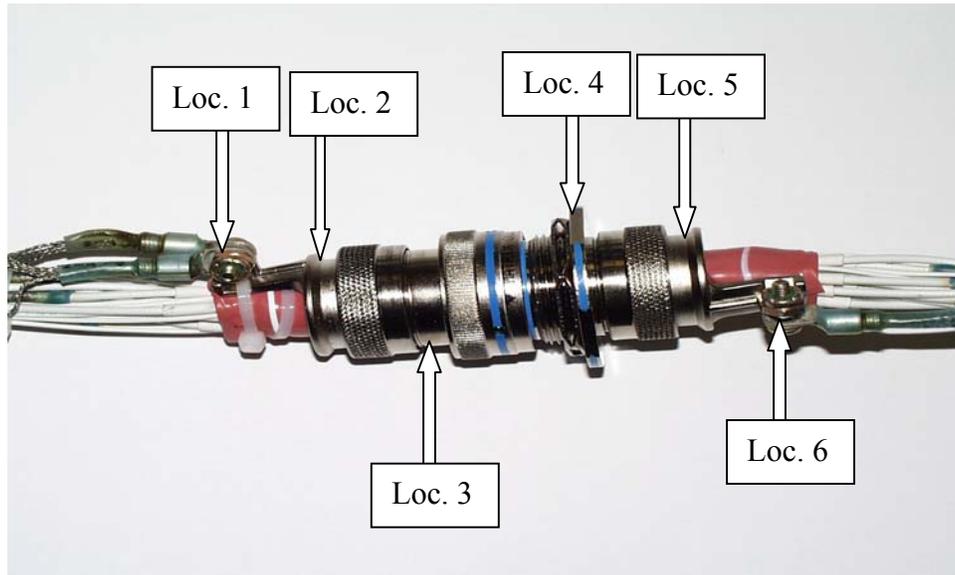


FIGURE 7. DIRECT CURRENT RESISTANCE TEST LOCATIONS
(CENTER CONNECTOR)

These locations define the following measurements.

- Measurement 1 was the resistance between shield termination (Loc. 1) and the backshell (Loc. 2) of a plug.
- Measurement 2 was the resistance between the backshell (Loc. 2) and the connector body (Loc. 3) of the plug.
- Measurement 3 was the resistance between the connector body of the plug (Loc. 3) and the bulkhead flange (Loc. 4) of the receptacle.
- Measurement 4 was the resistance between the bulkhead flange (Loc. 4) and the backshell (Loc. 5) of the receptacle.
- Measurement 5 was the resistance between the backshell (Loc. 5) and the shield termination (Loc. 6) of the receptacle.

Figure 8 specifies the resistance measurements at the plug connected to the termination box.

- Measurement 6 was the resistance between the shield termination (Loc. 7) and the backshell (Loc. 8) of the plug.
- Measurement 7 was the resistance between the backshell (Loc. 8) and the connector body (Loc. 9) of the plug.

- Measurement 8 was the resistance between the connector body (Loc. 9) of the plug and the termination box.

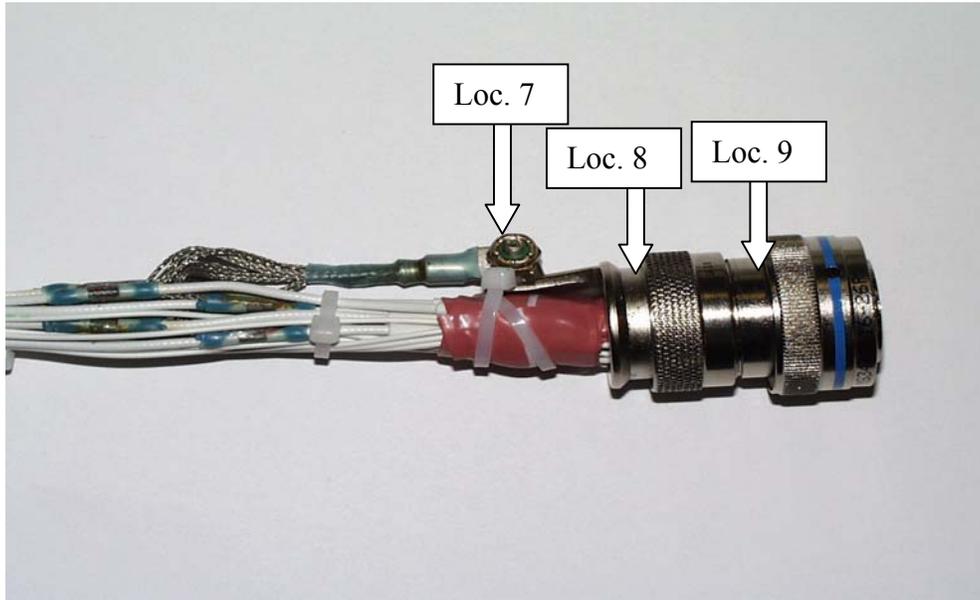


FIGURE 8. DIRECT CURRENT RESISTANCE TEST LOCATION (END CONNECTOR)

Shield resistance was also measured for individual and total wire bundles to calculate the loop resistances of loops 1 and 2 and the total loop.

- Shield resistance 1 was the shield resistance of the individual wire bundle terminating at the 0 k Ω box. The measurement was taken between the shield termination (Loc. 7) at the end connector disconnected from the 0 k Ω box and the shield termination (Loc. 6) of the center connector fixed onto the bulkhead.
- Shield resistance 2 was the shield resistance of the individual wire bundle terminating at the 10 k Ω box. The measurement was taken between the shield termination (Loc. 7) of the end connector disconnected from the 10 k Ω box and the shield termination (Loc. 1) of the center connector fixed onto the bulkhead.
- Total shield resistance was the shield resistance of the total wire bundle. The measurement was taken between the shield terminations at the two end connectors disconnected from their respective termination boxes.

3. FIELD SURVEY.

3.1 SYSTEM SELECTION.

The FADEC system was chosen to be the representative wire bundle for the field survey for the following reasons:

- Both newly manufactured and in-service aircraft, using the FADEC system, were available for study.
- The system contains both overbraided and pig-tail wire bundle shielding.
- There have been no major engineering changes over the past 5 years.

3.2 FULL AUTHORITY DIGITAL ENGINE CONTROL SYSTEM DESCRIPTION.

The aircraft engines, controlled by the FADEC system, use an electronic control based on two single-channel FADEC units that monitors and controls each engine. The FADEC is the controlling computer of the engine indicating and control system. There are two FADECs per engine. Each FADEC is mounted off the engine and has four electrical connectors. Two of the electrical connectors are used for data communication with the aircraft, such as the throttle lever angle, flight conditions from the air data computers, cockpit switch positions, data for the Engine Indication Crew Alert System, and electrical power. The third electrical connector is for communication with the other FADEC. The fourth electrical connector is connected to the engine.

3.3 TEST PROCEDURE.

The Boeing LRT and the network analyzer were used to perform the measurements on the aircraft. The test procedures for both the Boeing LRT and the network analyzer were mentioned in sections 2.1 and 2.3.

The following procedure was used to perform a visual inspection of the wire bundles.

- Inspect the bundles for any signs of chafing, rubbing, or tearing.
- Check for any films or deposits and evidence of corrosion on the connector and shield.
- Check the connector shields and bulkhead connectors for looseness.

3.3.1 Measurements on the FADEC Wire Bundles.

Measurements were taken on four newly built aircraft from the production center and on ten in-service aircraft from the service center. The measurements made on the newly built aircraft were used as a baseline for measurements made on the in-service aircraft. Out of 20 available locations on each aircraft for loop resistance measurement, there were a few locations under the baggage compartment that were not accessible while keeping the connectors intact. Those locations are mentioned in tables 1 and 2.

TABLE 1. LOOP RESISTANCE MEASUREMENTS ON FADEC WIRE BUNDLES OF IN-SERVICE AIRCRAFT

Aircraft Serial No.	001	002	003	004	005	006	007	008	008	009
AW Date	2/17/97	6/7/97	6/27/97	9/2/97	7/1/98	3/31/99	5/21/99	11/24/9	3/2/00	11/7/00
Field Survey Date	7/13/01	5/22/01	7/20/01	7/26/01	7/20/01	7/13/01	5/22/01	5/22/01	5/24/01	7/20/01
Aircraft Age (Yrs.)	4.4	4.0	4.1	3.9	3.1	2.3	2.0	1.5	1.2	0.7
Flight Hours	2523	2161	1062	3041	1467	2273	396	1803	1045	305
Left Engine:										
Blue Bundle	13.06	12.22	12.55	15.56	10.71	8.51	9.73	8.89	7.32	7.53
Yellow Bundle	14.74	12.06	11.48	10.85	10.98	9.38	8.7	9.3	8.57	8.01
Right Engine:										
Blue Bundle	9.73	8.81	40.52*	11.4	9.73	11.05	8.38	9.45	7.41	8.02
Yellow Bundle	11.34	8.72	13.51	11.18	10.5	10.06	36.9*	8.56	9.79	9.1
Average	12.22	10.45	12.51	12.25	10.48	9.75	8.94	9.05	8.27	8.17
Left FADEC A:										
Pk 003 (wire bundle)	**	19.18	21.11	**	11.76	**	**	16.04	10.89	14.19
Pk 005 (wire bundle)	20.45	16.17	12.98	12.03	14.71	9.17	19	19.24	10.14	10.16
Pk 007 (wire bundle)	**	**	**	15.66	21.55	37.05	11.4	8.14	8.5	10.11
Pk 009 (wire bundle)	34.17	25.59	35.12	24.23	21.45	**	23.15	22.14	21.55	21.23
Right FADEC A:										
Pk 004 (wire bundle)	**	19.01	**	**	**	14.4	**	15.71	**	**
Pk 006 (wire bundle)	10.58	32.17	9.86	7.92	13.1	6.69	7.03	9.91	7.33	2.4
Pk 008 (wire bundle)	**	16.86	**	12.79	17.17	**	8.76	9.88	9.06	17.46
Pk 010 (wire bundle)	25.99	22.83	23.94	21.55	23.24	19.01	22.87	19.98	19.67	19.42
Left FADEC B:										
Pk 013 (wire bundle)	15.16	34.59	17.59	**	12.12	12.1	14.42	14.88	**	11.04
Pk 015 (wire bundle)	12.14	21.89	10.23	9.82	10.22	7.07	25.59	24.04	18.5	6.09
Pk 017 (wire bundle)	**	24.11	**	9.58	13.82	**	**	9.04	14.6	**
Pk 019 (wire bundle)	23.6	21.67	20.59	22.07	23.3	**	24.69	19.53	16.85	19.27
Right FADEC B:										
Pk 014 (wire bundle)	**	**	**	**	**	**	**	**	11.64	**
Pk 016 (wire bundle)	11.02	18.06	10.61	11.47	9.75	6.35	5.84	9.88	12.96	5.1
Pk 018 (wire bundle)	**	**	**	**	**	**	**	**	**	**
Pk 020 (wire bundle)	12.18	20.64	22.1	19.61	24.74	16.85	17.55	16.07	19.95	15.61

**Inaccessible wire bundles for loop resistance measurements.

TABLE 2. LOOP RESISTANCE MEASUREMENTS ON FADEC WIRE BUNDLES OF NEW PRODUCTION AIRCRAFT

Aircraft Serial No.		101	102	103	104
Field Survey Date		7/26/2001	4/16/2001	4/17/2001	4/17/2001
Left Engine	Blue Bundle	7.76	7.52	7.32	7.8
	Yellow Bundle	8.68	8.78	7	8.7
Right Engine	Blue Bundle	7.42	7.75	7.4	7.5
	Yellow Bundle	8.62	9.03	8.81	8.39
Average		8.12	8.27	7.63	8.10
Left FADEC A (wire bundle)	Pk 003	12.77	7.32	10.37	**
	Pk 005	7.25	5.47	5.2	5.82
	Pk 007	13.87	7.34	36.06	3.94
	Pk 009	23.15	22.28	20.06	21.58
Right FADEC A (wire bundle)	Pk 004	**	7.47	**	10.89
	Pk 006	8.18	9.62	4.22	8.35
	Pk 008	14.05	3.96	**	25.01
	Pk 010	20.07	17.61	19.1	18.78
Left FADEC B (wire bundle)	Pk 013	9.96	8.74	**	9.09
	Pk 015	6.1	5.29	3.61	3.7
	Pk 017	**	11.7	4.7	4.9
	Pk 019	19.1	17.88	20.49	18.37
Right FADEC B (wire bundle)	Pk 014	**	**	**	**
	Pk 016	8.32	5.59	4.82	3.77
	Pk 018	**	**	**	**
	Pk 020	16.42	14.45	14.84	16.09

**Inaccessible wire bundles for loop resistance measurements.

A total of 20 readings were taken on each aircraft during the field survey. There were four connectors on each FADEC unit, and four units were installed on each aircraft. Therefore, 16 measurement locations were available on the FADEC units, as shown in figure 9. The other four readings were taken on the engines where two wire bundles on each engine were associated with the FADEC system. Figure 10 shows one of the measurements taken on the FADEC unit under the baggage compartment of the aircraft. However, if the harness has multiple branches, as shown in figure 11, a loop resistance measurement should be made on each branch to determine viability of the entire harness.

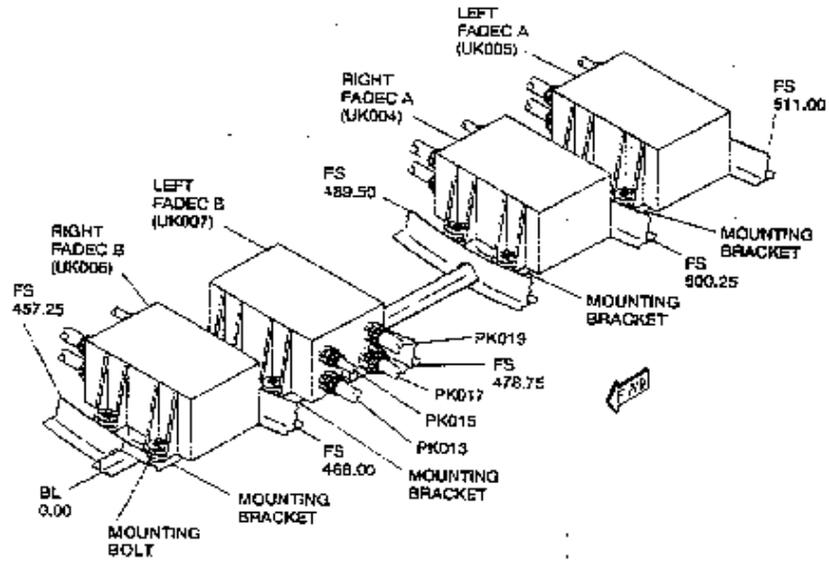


FIGURE 9. LOCATIONS OF FADEC UNIT MEASUREMENTS



FIGURE 10. LOOP RESISTANCE TESTER MEASUREMENTS ON FADEC UNIT



FIGURE 11. THE FADEC WIRE HARNESS

3.3.2 Measurements.

The results obtained after the tests are shown in table 1 for in-service aircraft and in table 2 for production aircraft. The loop resistance values measured at different locations on the FADEC system of each aircraft were also recorded. The loop resistance values of the shields show a variation with the age of the aircraft. They also show a variation with the number of flight hours on the aircraft. However, in the case of newly built aircraft, no considerable variance in the values of loop resistance, between aircraft, was observed.

The average values of loop resistance of the FADEC wire bundles increased from 8 milliohms at the time of manufacture to over 12 milliohms when the harness in the aircraft was 4 or more years old, as plotted in figure 12. FADEC loop resistance variation is plotted against the aircraft flight hours, as shown in figure 13. Here again, loop resistance increased from 8 to over 12 milliohms on aircraft with over 3000 hours of flight time. The correlation coefficient calculated between the harness age in the aircraft and the loop resistance was 0.935, while that between flight hours and the loop resistance was 0.683.

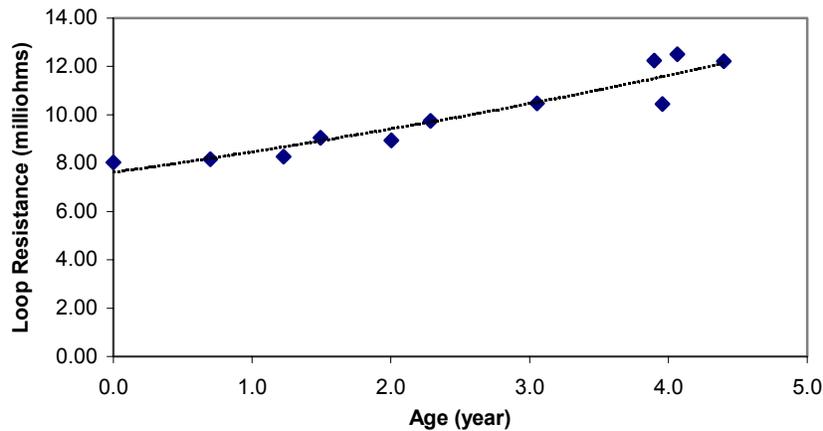


FIGURE 12. THE FADEC HARNESS LOOP RESISTANCE VS AGE OF THE AIRCRAFT

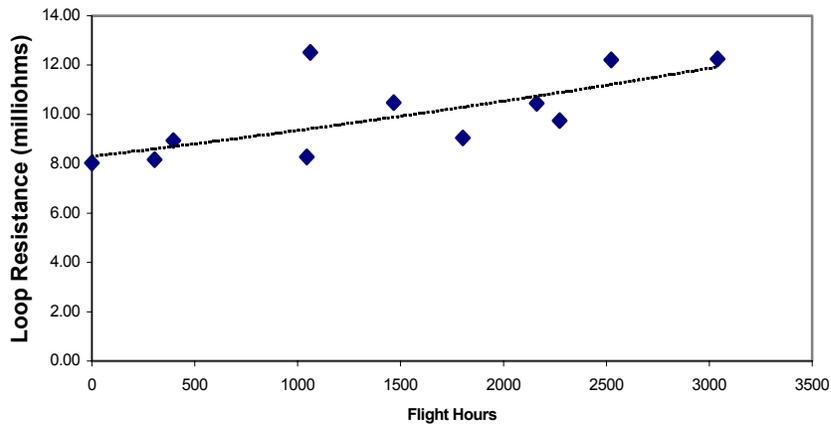


FIGURE 13. THE FADEC HARNESS LOOP RESISTANCE VS FLIGHT HOURS ON THE AIRCRAFT

As shown in these figures, the correlation between the loop resistance and harness age is stronger than the correlation between the loop resistance and the number of aircraft flight hours. This is an interesting result, and further study is warranted as to the reason why. If the single FADEC loop resistance data point of 12.51 milliohms with only 1062 aircraft flight hours was ignored, then the FADEC loop resistance could be approximated using a linear combination of harness age and aircraft flight hours.

During the field survey, a visual inspection of the wire bundles was performed before the start of each test. No physical variation was observed on any wire bundle, and no deposits or traces of corrosion were found on the connectors or shields of any wire bundle.

3.3.3 Observations.

The following observations were made based on experimental data analysis and visual inspection:

- No change in the physical condition of the FADEC wire bundles was observed in any of the newly built or in-service aircraft tested.
- The field survey data indicated that the average shield loop resistance of FADEC wire harnesses measured in the business jet aircraft increased 50% from 8 milliohms, at the time of manufacture, to over 12 milliohms on aircraft with 2500 or more flight hours, as well as for those aircraft where the harness was 4 or more years old.
- The change in loop resistance of FADEC wire harness shielding correlated better with aircraft age (0.94) than it did with aircraft flight hours (0.68). Although the increase in the loop resistance was small and within tolerance, this is a significant result and further study may be warranted as to the nature and cause of this increase.

4. COMPARISON OF IMPEDANCE MEASUREMENTS TECHNIQUES AND NETWORK ANALYZER RESULTS.

The Boeing and the Airbus LRT measurements were compared with the network analyzer readings to evaluate their performance and accuracy. The dc resistance of the shield was also measured using a Keithley Model 580 Micro-Ohmmeter. The network analyzer was used to determine the loop impedance response over the range of frequencies selected from 10 Hz to 10 MHz. The results at a frequency of 200 Hz and 1 kHz were used to verify the Boeing and the Airbus loop resistance readings, respectively. Measurements were made on both wire bundle shields on laboratory test panels and on actual in-service aircraft FADEC harness shields during the field survey, and then compared.

4.1 COMPARISON OF MEASUREMENTS ON ACTUAL AIRCRAFT WIRING.

The study used the data from the field survey of production and in-service aircraft. The measurements were taken on both the blue and the yellow FADEC cables connected to each engine using a Boeing LRT. Figure 14 shows an example of the Boeing LRT measurements on the FADEC cables.



FIGURE 14. BOEING LRT MEASUREMENTS ON THE FADEC WIRE BUNDLES

Readings were taken using the network analyzer on these same cables at the same locations and compared with the readings taken using the Boeing LRT. Figure 15 shows an example of the probe setup for making measurements using the HP network analyzer on the FADEC cables.



FIGURE 15. NETWORK ANALYZER MEASUREMENTS ON THE FADEC WIRE BUNDLES

4.1.1 Measurements.

The LRT was more practical to use when compared to the network analyzer for making measurements on actual aircraft. As compared to the network analyzer, which required additional equipment (current injection probe, Pearson probe, and leads) for making measurements, the LRT was easier to carry and simpler to use. The difficult setup of the network analyzer made its use complicated for the field measurements. As mentioned in section 3, the swept frequency of the network analyzer provided no useful advantage over the LRT because the impedance is almost entirely resistive from dc to over 1000 Hz.

Table 3 shows a measurement comparison of the Boeing LRT and the HP network analyzer on actual aircraft. The Boeing LRT measurements concur well with the network analyzer readings for all four wire bundles on the two engines. The percentage difference between the Boeing LRT and the network analyzer measurements ($\Delta\%$) was also tabulated. The maximum difference was 7.9%, which shows the accuracy of the Boeing LRT when compared to the network analyzer for field measurements.

The data in table 3 is plotted in figure 16. The graph is quite flat, which means that there is no considerable difference between the two measurement techniques.

TABLE 3. MEASUREMENT COMPARISON OF LRT AND NETWORK ANALYZER ON AIRCRAFT

Measurement Technique	Engine 1		Engine 2	
	Blue Cable (m Ω)	Yellow Cable (m Ω)	Blue Cable (m Ω)	Yellow Cable (m Ω)
Boeing LRT (resistance)	7.99	12.89	7.75	9.03
Network analyzer (impedance)	8.2	14.0	7.8	8.96
$\Delta\%$	2.56	7.9	0.64	0.78

Note: The network analyzer readings were taken at 200 Hz for comparison with LRT measurements.
 $\Delta\%$ = Percentage difference from network analyzer measurements.

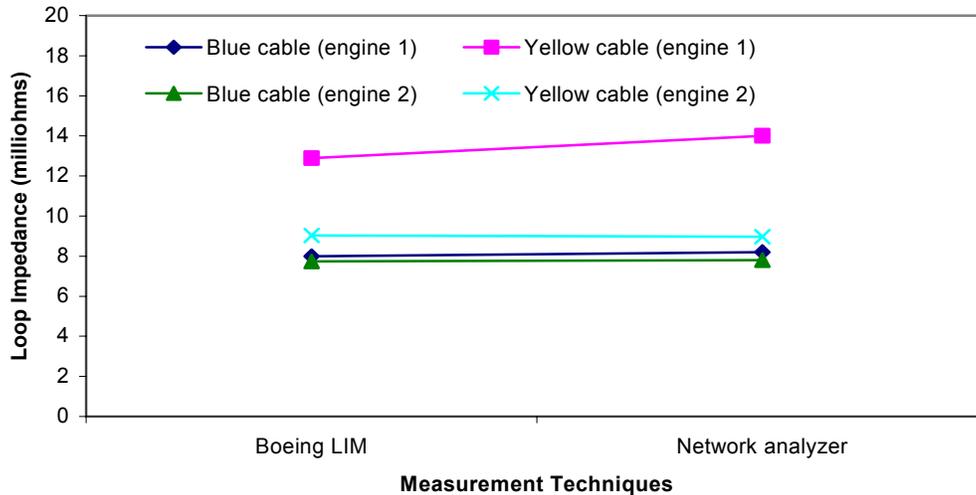


FIGURE 16. COMPARISON OF LRT AND NETWORK ANALYZER MEASUREMENTS ON AIRCRAFT FADEC SYSTEM

4.1.2 Observations.

- The Boeing LRT provided the same resistance values as the network analyzer, indicating that either instrument could be used to make the same measurements.

- The LRT is more practical for field survey than the network analyzer because it is portable, simple to use, and takes less time for measurements. However, both techniques require a skilled operator to make the measurements.

4.2 COMPARISON OF MEASUREMENTS ON LABORATORY TEST PANELS.

The relevant data from the laboratory tests of the shielded wire bundles of this research has been included as part of this study. The loop resistance measurements for the total harness shield loop were taken on all six test panels using the Boeing LRT and the network analyzer before and after shield degradation. Loop resistance (and network analyzer swept-frequency impedance) measurements were also taken using the Boeing LRT, the Airbus LRT, the network analyzer, and the Keithley Model 580 Micro-Ohmmeter to provide a better measurement comparison for all the techniques. These measurements were taken on loops 1 and 2 of control test panel A6. Figures 17 and 18 show the loop resistance measurements using the Boeing LRT and the network analyzer.



FIGURE 17. INDIVIDUAL LOOP RESISTANCE MEASUREMENT USING THE LRT



FIGURE 18. INDIVIDUAL LOOP IMPEDANCE MEASUREMENT USING THE NETWORK ANALYZER

4.2.1 Resistance-Inductance-Resistance Modeling for Test Panels.

The loop impedance values for all test panels, as measured by the network analyzer, were modeled with a passive circuit consisting of two resistors and an inductor. The passive circuit was designed with a small resistance in series with an inductor, both in parallel with a relatively large resistor, as shown in figure 19. The series resistance (R_s) was chosen close to the measured loop impedance values at lower frequencies (10 Hz to 1 kHz). The parallel resistor (R_p) was selected to reduce the minimal variation between the experimental impedance values and the model values at higher frequencies. The error between the two graphs remained less than 5% over the entire range of frequencies.

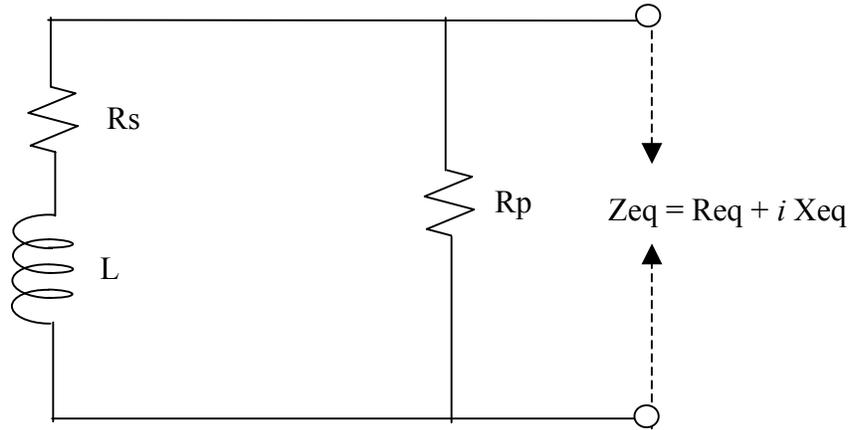


FIGURE 19. CIRCUIT DIAGRAM FOR R-L-R MODELING

The loop impedance values measured at baseline and after degradation testing were modeled with the resistance-inductance-resistance (R-L-R) circuit. The impedance (Z_{eq}) was calculated as follows:

$$|Z_{eq}| = \sqrt{(R_{eq})^2 + (X_{eq})^2}$$

where

$$R_{eq} = \frac{R_s R_p (R_s + R_p) + R_p X_L^2}{(R_s + R_p)^2 + X_L^2}$$

$$X_{eq} = \frac{X_L R_p (R_s + R_p) + R_p X_L R_s}{(R_s + R_p)^2 + X_L^2}$$

and

$$X_L = 2\pi f L$$

The modeling was done to observe the behavior of the shield impedance over a range of frequencies (10 Hz to 10 MHz). An increase in the shield impedance could be a result of a resistive change, an inductive change, or a combination of both. This modeling helped in determining the type of change that caused an increase in the loop impedance after the test panels were subjected to various degradation tests.

4.2.2 Measurements.

The results of the comparison study of various measurement techniques are shown in tables 3 through 6. Table 3 shows a measurement comparison of the Boeing LRT and the network analyzer on actual aircraft. Table 4 lists the loop resistance values obtained by using the Boeing LRT (fixed at 200 Hz), the network analyzer (set at 200 Hz), and the Keithley Model 580 Micro-Ohmmeter for test panels type A. Table 5 lists the loop resistance values obtained by using the Boeing LRT (fixed at 200 Hz) and the network analyzer (set at 200 Hz) for test panels type B. Table 6 shows a comparison of all the measurement techniques, which includes the Boeing LRT, the Airbus LRT, the network analyzer, and the Keithley Model 580 Micro-Ohmmeter, that were taken on test panel A6. The network analyzer readings were taken at 1 kHz and 200 Hz to make a comparison with the readings taken using the Airbus and Boeing LRTs. All the tables (3-6) show that the LRT readings are very close to the network analyzer readings. The slight difference in measurements between the two techniques is because the LRTs provide loop resistance while the network analyzer provides the loop impedance over a range of frequencies. The dc measurements are less than the readings taken from other techniques since the ground plane resistance was not incorporated in the loop resistance measurement.

TABLE 4. LOOP RESISTANCE COMPARISON USING DIFFERENT TECHNIQUES AT BASELINE AND HIGH TEST LEVELS FOR TEST PANELS TYPE A

Test Type	Test Level	Boeing LRT (mΩ)	R-L-R Modeling Rs (mΩ)	Network Analyzer (mΩ)	Keithley Model 580 Micro-Ohmmeter (mΩ)
Temp/Alt	Baseline	10.26	10.75	10.75	8.73
	High	14.38	14.9	14.84	9.48
Salt Spray and Humidity	Baseline	9.41	9.75	9.765	8.51
	High	11.44	12.2	12.21	8.84
Mechanical Degradation	Baseline	9.17	9.3	9.43	8.14
	High	10.36	11	11.12	9.34
Vibration	Baseline	9.48	9.8	9.88	
	High	9.9	10.9	10.27	
Combination	Baseline	9.4	9.75	9.69	
	High	16.02	16.6	16.31	13.65

TABLE 5. LOOP RESISTANCE COMPARISON USING DIFFERENT TECHNIQUES AT BASELINE AND HIGH TEST LEVELS FOR TEST PANELS TYPE B

Test Type	Test Level	Boeing LRT (mΩ)	R-L-R Modeling Rs (mΩ)	Network Analyzer (mΩ)
Temp/Alt	Baseline	60.71	61	61.45
	High	70.68	77.25	76.95
Salt Spray and Humidity	Baseline	39.57	40	39.35
	High	40.25	40	39.03
Mechanical Degradation	Baseline	68.72	77	76.92
	High	149.26	153	152.2
Vibration	Baseline	*	*	*
	High	*	*	*
Combination	Baseline	*	*	*
	High	*	*	*

*Test data could not be collected due to connector failures for type B test panels.

TABLE 6. COMPARISON OF LOOP RESISTANCE VALUES USING DIFFERENT TECHNIQUES (Laboratory test panel A6)

Measurement Techniques	Loop 1	Loop 2
Boeing LRT	10.05	9.62
Airbus LRT	12.3	11.5
Network Analyzer (200 Hz)	11.68	9.59
Network Analyzer (1 kHz)	12.716	10.313
Keithley Model 580 Micro-Ohmmeter	9.38	8.86

Figure 20 shows a typical impedance versus frequency curve, taken from the network analyzer, during testing. The values for Rs, inductor (L), and Rp for both baseline and posttest models, are also given on this graph. The data was taken before and after the temperature and altitude degradation tests. The flat portion of the curves, at frequencies less than 1 kHz, indicate that the analyzer is measuring the resistance of the shielding, whereas the rising portion of the curve, at frequencies greater than 3 kHz, indicate that the analyzer is measuring the inductance and ac resistance of the shield. As shown in the figure, the change from before to after the degradation occurred in the shield's resistance, or in frequencies less than 1 kHz. This is also evident from the change observed in the value of Rs from the baseline model to the posttest model. The value for the inductor in the model circuit remained constant. This was the characteristic of all the

degradation tests (except for the mechanical degradation tests on panel B1) and shows that the loop resistance is what is indicative of shield degradation. During the mechanical degradation on test panel B1, which involved cutting the shields, there was an obvious increase in the loop impedance for the entire swept frequency (figure 21) from baseline to final testing. This is also evident from the change in the values of both R_s and L from the baseline model to the posttest model for test panel B1. In order to find any possible advantage of this increase in the inductive portion, a statistical analysis was done to calculate means and standard deviations. This could be beneficial in helping to easily detect a floating shield wire at higher frequencies, as it is the only case where there was an inductive change. Table 7 shows the averages and standard deviations calculated for the loop impedance values taken at 200 Hz and 300 kHz for all test panels. The standard deviation, with respect to the average calculated at 300 kHz, is found to be less compared to the values at 200 Hz. Since all the loop impedance values at 300 kHz are tightly clustered around the mean, a generic impedance value at a higher frequency could be established as a baseline for the same type of wire harnesses. Therefore, any drastic increase in loop impedance from the generic baseline will indicate a floating shield wire. The reason for establishing a generic baseline on the test panels might be because the wire harnesses are at a constant distance from the ground plane, but aircraft wire harnesses are usually laid down along the plane. Therefore, a skewed distribution around the mean might not be possible in the case of aircraft wire harnesses. Hence, this study provides evidence that the LRTs, which measure the resistance of the shielding, are as good as a network analyzer for indicating shield degradation.

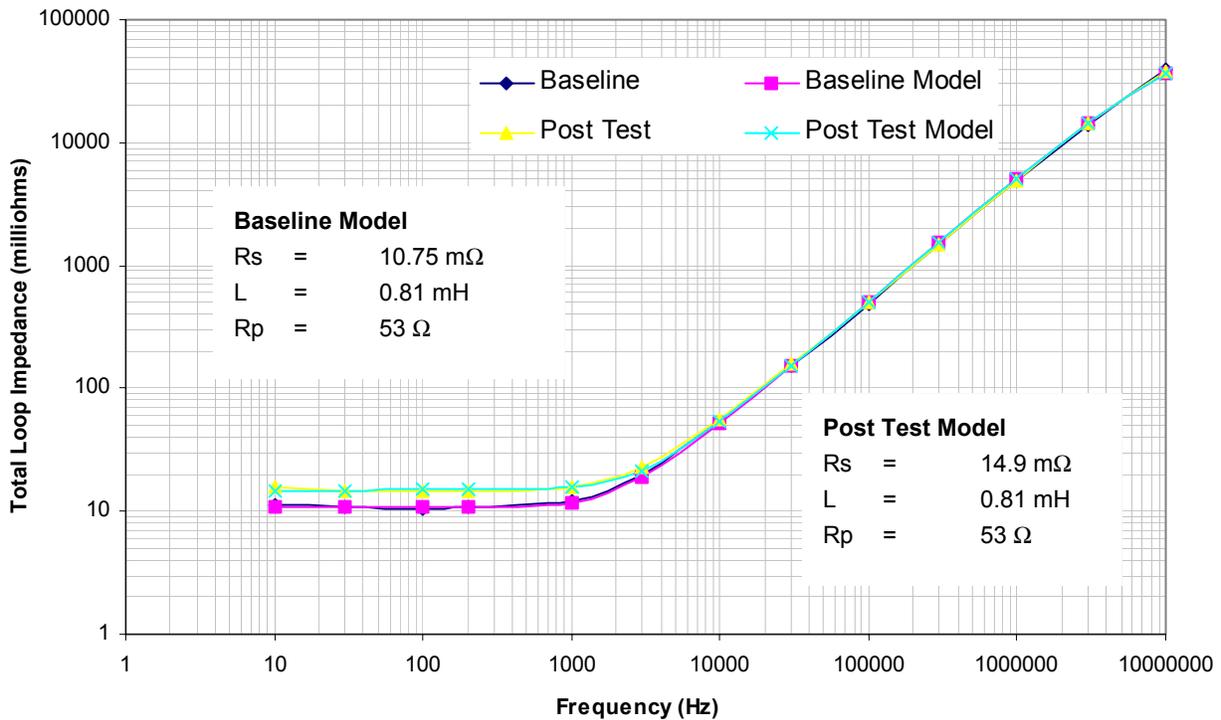


FIGURE 20. EXAMPLE OF TOTAL LOOP IMPEDANCE CHARACTERISTICS BEFORE AND AFTER DEGRADATION TEST USING THE NETWORK ANALYZER

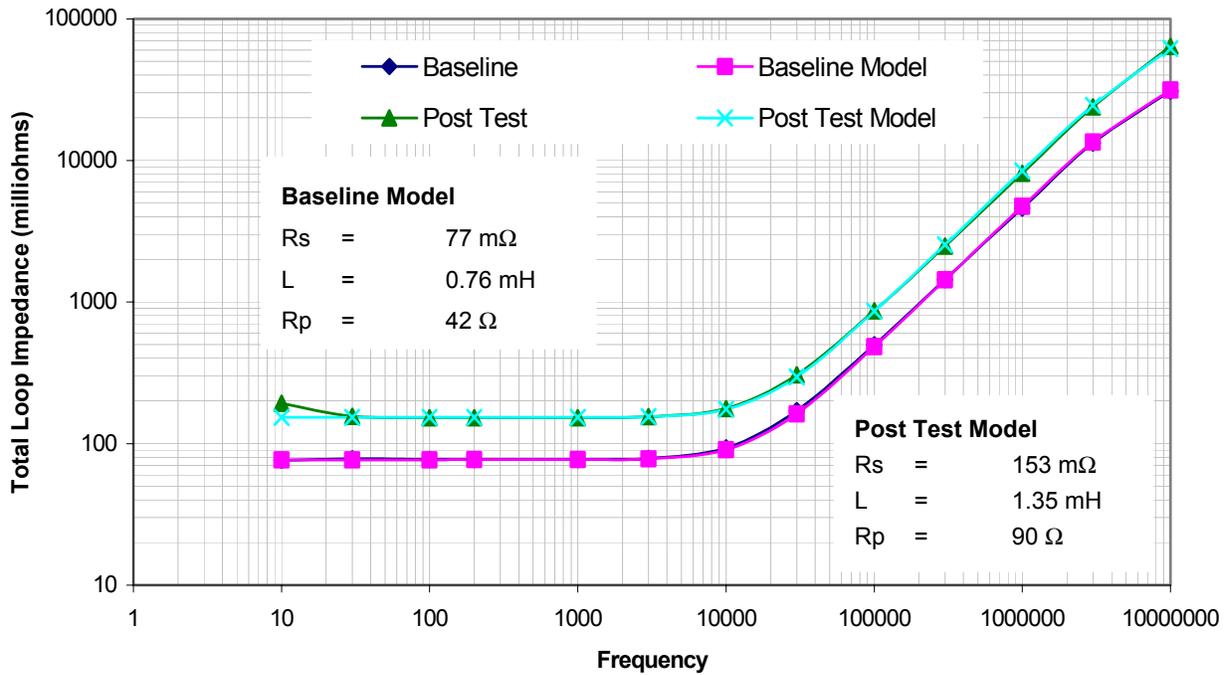


FIGURE 21. TOTAL LOOP IMPEDANCE CHARACTERISTICS BEFORE AND AFTER MECHANICAL DEGRADATION TEST (TEST PANEL B1)

TABLE 7. STATISTICS OF NETWORK ANALYZER MEASUREMENTS AT 200 Hz AND 300 kHz

Network Analyzer	200 Hz	300 kHz
Average of baseline readings of all test panels	26.365	1472.69
Standard deviation	23.68	48.53

The graphs in figures 22 and 23 represent the data given in tables 1 through 3. Figure 22 is a plot of the total loop resistance measured by the different techniques at a high-severity level for all degradation tests. Figure 23 shows the individual loop resistances measured by all four techniques. The graphs in both figures are quite flat, which again shows that the LRT will provide loop resistance that would give a similar indication of shield degradation as loop impedance would in the case of the network analyzer.

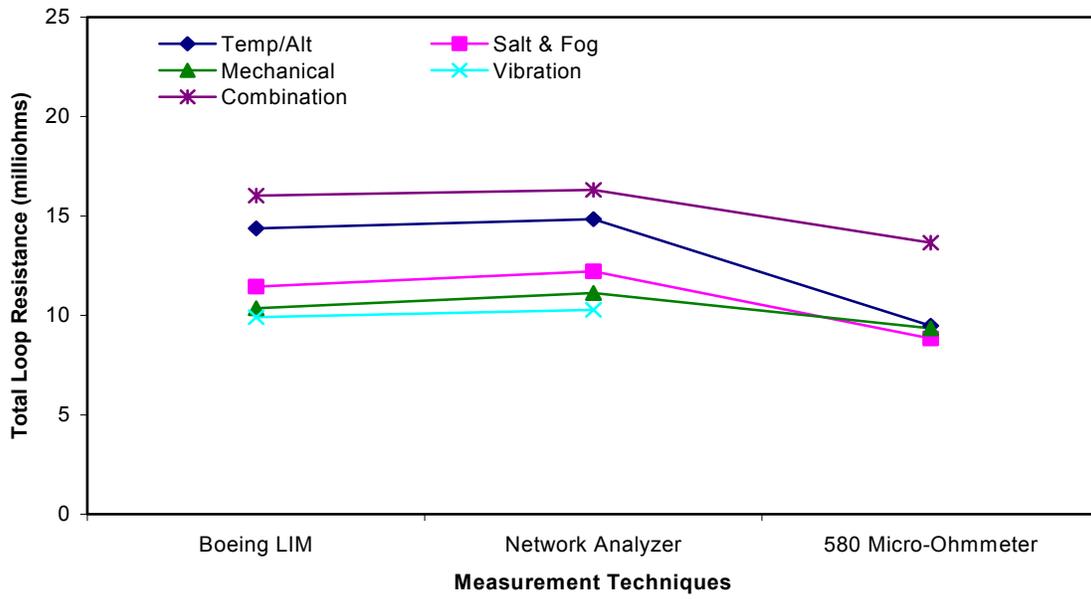


FIGURE 22. LOOP RESISTANCE COMPARISON AT A HIGH-SEVERITY TEST LEVEL

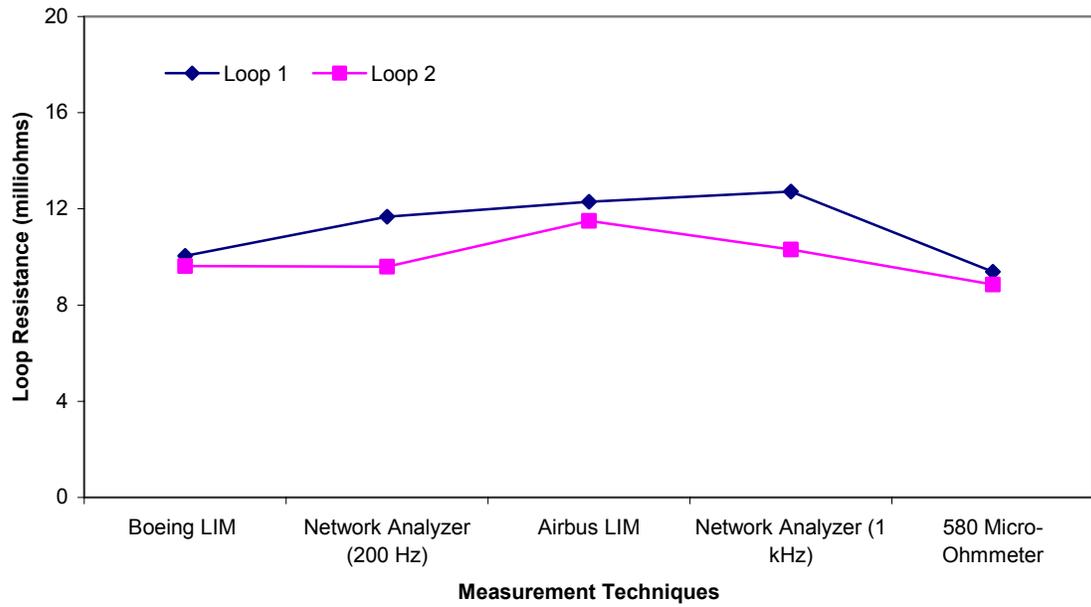


FIGURE 23. LOOP RESISTANCE USING DIFFERENT MEASUREMENT TECHNIQUES

4.2.3 Observations.

The following observations were made based upon the experimental data analysis.

1. The LRT gives loop resistance results at a fixed frequency, and the network analyzer gives loop impedance over a range of selected frequencies. However, no significant advantage was found in sweeping the frequency.
2. The R-L-R modeling analysis showed that the increase in the loop impedance, due to shield degradation, was mainly due to the resistive increase of the impedance. The LRT can only detect an increase in the resistance of the loop, whereas a network analyzer could detect an increase in either or both resistance and inductance of the loop. Since changes in the shield loop impedance are largely resistive below 1500 Hz, the LRTs operating at 200 or 1000 Hz were as effective as the network analyzer in detecting the shield degradation.
3. The Boeing and the Airbus LRTs were equally effective in measuring any change in the loop resistance values. Therefore, either one can be used to measure shield integrity and degradation.

5. OVERALL OBSERVATIONS.

The following observations were made based upon the loop resistance tester (LRT) and the network analyzer measurements obtained from laboratory tests and the field survey:

1. The field survey data indicate that the loop resistance of wire harnesses increased 50% with aircraft age and also with the number of aircraft flight hours. The change in the loop resistance of wire harness shielding correlates better with aircraft age (0.94) than it does with aircraft flight hours (0.68).
2. The LRTs measure the resistance of the loop at a fixed frequency. However, the network analyzer can measure impedance over swept frequencies. In this study, the change in the loop impedance, due to degradation, was observed as a result of an increase in the resistive part of the impedance only. Therefore, the LRTs were as effective as the network analyzer in detecting the shield degradation.
3. The LRT was more practical for field survey than the network analyzer because it was portable, simpler to use, and it took less time for measurements. However, both the techniques required a skilled operator to make the measurements.
4. The LRT could be used in defining repeatable standards for loop resistance measurements involved in an actual aircraft for wire bundle shielding. This could only be performed on wire bundles that ran straight from one end to another. However, complications may arise in the case of measurements to be made on wire bundles that have several branches. To measure the shield integrity of a branching harness, each branch should be measured individually.

5. A connector backshell loosening study appears warranted to measure shield degradation effects and compile maintenance procedures.

6. REFERENCES.

1. Eric L. Godo and Bruce V. Deventer, "Loop Resistance Tester: A Non-intrusive Method to Measure Connector and Shield Resistance," *IEEE Journal*, 1998.
2. Eric L. Godo and Matt Taorima, "Loop Resistance Tester," *Aero magazine*, No. 10, March 2000.
3. Airbus UK LTD, "Loop Resistance Tester TS11194 Instruction Manual," B21/DOC/2002.

7. GLOSSARY.

Airworthiness Date (AWD)—The date on which it is determined whether an aircraft or one of its component parts meets its type design and is in a safe condition to fly.

Baseline Testing—The initial testing that is done on the test panels before they are subjected to any further degradation tests.

Boeing Loop Resistance Tester (LRT)—A Boeing Loop Resistance Tester is a portable electrical device that measures the resistance (at 200 Hz) of a loop of conductive material without disturbing or disconnecting the loop. It is typically used in industry to measure the shield loop resistance of an aircraft harness or wire bundle with two clamp-on probes without disturbing or removing any of the harness connectors or backshells. One probe is used to induce a known current in the loop. The other probe is used to measure the resulting voltage from which the loop resistance may be determined. It may also be used in joint mode to measure the resistance between components of the harness and structure.

Correlation—A measure of how close two variables change in value with respect to one another or with time.

Drive Coupler—The drive coupler is one of the four elements in a Boeing LRT, which drives (induces) a voltage around the loop being measured.

Full Authority Digital Electronic Control (FADEC) System—The FADEC system is a computer that monitors and controls each engine.

Field Survey Date—The date on which a field survey of a FADEC system was conducted.

Network Analyzer—A network analyzer is an electronic device used to measure electrical impedance over a wide range of frequencies. Using a pair of clamp-on probes, a Hewlett-Packard network analyzer was used to determine the shield loop impedance of the test wire bundles over a range of frequencies selected from 10 Hz to 10 MHz in this study.

Overbraided Wire Bundle—A wire bundle whose length is entirely covered (shielded) with an outer woven braid of fine-tinned copper wires.

Shield—A conductor that is grounded to an equipment case or aircraft structure at both ends and is routed in parallel with, and bound within, a cable wire bundle. It usually is a wire braid around some (or all) of the wires or cables in the cable bundle. Or it might be a metallic conduit, channel, or wire, grounded at both ends within the cable bundle. The effect of the shield is to provide a low resistance path between equipment so connected.

Shielded Wire Bundle—A wire bundle that contains one or more shields.

Sense Coupler—One of the four elements in a Boeing LRT that senses the current flowing in the loop to measure shield loop impedance.

Test Panel—An aluminum panel with cable termination boxes and brackets attached. Panels were constructed for this study to simulate an aircraft structure and act as a ground plane and mount for the cable wire bundles.

Visual Inspection—Procedure adopted to check for physical degradation.

Wire Bundle—A group of wires routed together that connect two pieces of equipment.